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MOIRE FOR DYNAMIC FRACTURE

by

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1. Objective

The objective of this research program is to investigate experimentally the transient strain and stress distributions in the vicinity of a running crack in engineering materials.

2. Precis of Significant Accomplishments

ONR Research Grant No. N00014-89-J-1276 commenced on November 1, 1988, to continue the study of dynamic crack propagation in real engineering materials. The sensitive Moire interferometry as well as the traditional geometric moire was used to analyze dynamic crack propagation in somewhat brittle material and rapid tearing in ductile material. A specially configured image converter camera, i.e., a four-frame IMACON 790 camera, was used to record the transient Moire interferometry patterns corresponding to either u- and/or v-displacement fields surrounding a rapidly propagating brittle crack in Homalite SEN specimens. Of the two displacement fields, the u-displacement field provided a more accurate dynamic stress intensity factor, K_I^{dyn}, and remote stress component, σ_{ox}. The σ_{ox}, which is identified in today's nomenclature as the T-stress component, together with K_I^{dyn} controlled the directional stability of a propagating mode I crack.

Effort was also expended in developing a Moire interferometry technique suitable for both small and large deformations. The composite grating (UWA/DME/TR-87/57), which was used to measure strains up to two to three percent, was one such effort At larger strains, however, the Moire grating loses its diffractive capability and geometric Moire becomes an attractive alternative*. Geometric Moire was thus used to record the vertical and horizontal displacement fields associated with stable crack growth of 10 - 20 mm in 2024-T3 aluminum SEN specimens. To no surprise, the J-integral was not path independent for crack extension in excess of 2 mm. The HRR v-displacement, which was computed by using the near-field J-integral, was in reasonable agreement with the measured v-displacement at distance of $r > 6$ mm from the crack tip but no such agreement was found with the HRR u-displacement.

* The first ONR technical report of 1965 dealt with the use of geometric Moire for transient analysis of fracturing epoxy plates.

Effort was also expended in developing an analytical procedure for predicting axial crack propagation and arrest in a pressurized airplane fuselage. The crack curving and hence the crack arrest potential of a rapidly propagating axial crack along a multiple site damage (MSD) in a fuselage lap joint was considered. The crack curving criterion, which was developed under a previous ONR contract (TR No. 41, October 1981 and TR No. 42, November 1981), together with a large deformation elastic-plastic finite element code was used to assess the capability of a tear strap for deflecting the propagating axial crack. Two ONR Technical Reports were written and an elastic crack propagation and kinking criterion in the presence of mixed modes I and II stress intensity factors was proposed. Self-similar crack extension was postulated when $K_I > K_{Ic}$, despite the presence of a substantial K_{II}, in order to account for the extensive crack extension in the Aloha Airlines B737-200 fuselage failure. These reports were instrumental in part, for a FAA grant on "Axial Crack Propagation and Arrest in Pressurized Fuselage."

The Dadkhah data (1988) was also re-analyzed to provide an experimental justification of the two-parameter, J-T and J-Q ductile fracture theories. The second order displacement components in the J-T and J-Q theories were obtained by subtracting the previously derived HRR displacements from the measured crack-tip displacements. The second order v-displacement was an order of magnitude smaller than the corresponding second order u-displacement which was nearly equal to the HRR u-displacement but negative in value. Moreover, the second order u-displacement exhibited a weak singularity of $r^{-0.05}$ for the 2024-0 aluminum specimen and would have resulted in a second order strain singularity of $r^{-1.05}$. This is a stronger singularity than the corresponding HRR u-displacement and violates the basic premise of the asymptotic solution, which is the basis of the J-T and J-Q theories, for the crack tip stress field.

In order to extend Moire interferometry into the ductile fracture domain, which heretofore was covered by geometric Moire, a new procedure for measuring large strains in the vicinity of a crack tip was developed in 1993 (UWA/DME/TR-93-73). The method uses a low-spatial frequency, i.e. from 160 lines/mm to 10 lines/mm and a steep grating on a mirror-finished specimen surface to achieve high contrast Moire fringes. A special four beam Moire interferometry bench was designed and constructed for use with this low frequency grating This procedure has been used exclusively in our dynamic ductile fracture studies since 1993.

Also Moire interferometry with two line densities of 1200 and 40 lines per mm was used to analyze a stationary and stably extending crack in thin 2024-T3 aluminum, single edge notched (SEN) specimens (UWA/DME/TR93-72) J-integral values for various integration contours were computed from these Moire displacement fields during crack tip blunting and subsequent crack extension. As expected, the near- and far-field J-integral values prior to stable crack growth coincided with the LEFM strain energy release rate, *G*, and validated the experimental procedure. The far field J increased but the near field J decreased continuously with increasing stable crack growth. The HRR displacement field, which was computed from the experimentally determined far-field J, agreed with the measured displacements prior to stable crack growth. However, these HRR displacements progressively deviated from the measured values with increasing crack extension. The results of this and previous studies showed that in the presence of stable crack growth under a state of plane stress, the J-estimation procedure in the EPRI Elastic-Plastic Fracture Analysis Handbook grossly over estimates the crack-tip J value and the HRR field was not detectable.

A numerical analysis was also conducted by inputting the measured displacements along a cross section of 41.6 (height) x 25.4 (width) mm straddling the crack with a finite element (FE) code based on the theory of incremental plasticity. The J integrals were evaluate along the same contours used in the experiments. Both plane strain and plane stress states were analyzed and the plane stress results were compared with the experimental results. The experimentally and numerically determined plane stress J integral values, with crack extension, were in good agreement with each other. The computed plane strain J-integrals were larger than the plane stress counterparts and showed a similar trend of decreasing J-values with decreasing contour sizes. These plane stress and plane strain results are in qualitative agreement with the finite element (FE) results by Brock and Yuan [1] for a nickel alloy CT specimen.

The measured crack tip opening angle (CTOA), which is the angle from the crack tip to the crack opening displacement (COD) 1 mm away, initially increased and then remained at a lower constant value throughout crack extension. This trend is consistent with the experimental results of Dawicke et al. [2]. The CTOA computed by the near-field J is in reasonable agreement with its measured counterpart.

Recent results by Sutton and Chao et al [3] at the University of South Carolina and Chiang [4] at SUNY Stony Brook using different experimental techniques are in essential agreement with our results. With these added experimental verifications, the ASTM procedure, which is based solely on the far field J integral value for evaluating the J resistance, J_R, is fundamentally flawed since J ceased to characterize the crack tip state.

More recently, 80 and 40 lines/mm Moire gratings were used to record the v-displacement fields of rapidly fracturing 7075-T6 and 2024-T3 aluminum SEN specimens of 1.6 mm thickness with an IMACON 790 camera. The hybrid experimental-numerical analysis was used to determine the dynamic fracture parameters which may control rapid fracture of ductile materials. The transient displacement field surrounding a rapidly propagating crack, which was recorded by Moiré interferometry, together with the crack extension history, was used to drive a dynamic elasto-plastic finite element (FE) model of the fracturing SEN specimen in its generation mode. The measured and computed crack tip opening angles (CTOA) coincided after dropping from an initial high value and remained constant during crack propagation. However, another study funded by FAA has shown that the CTOA is invariant with the thickness of the specimen and does not reflect the reduction in ductility with increased thickness of a fracture specimen..

As an alternative to the J-integral, the T^*_ε integral [5] which represents the energy dissipated in a narrow strip of width 2ε straddling the propagating crack was computed using the recorded transient displacements. The T^*_ε in this study increased to a constant value with crack propagation in contrast to the near-field J which decreased precipitously with crack extension. The T^*_ε versus crack velocity relation showed a stationary T^*_ε during the crack acceleration phase and the dynamic crack arrest T^*_ε was higher than the initiation T^*_ε. The results are consistent with the well-known K_{ID} versus crack velocity relation for brittle material. The dynamic arrest CTOA, on the other hand, was lower than the initiation CTOA and is inconsistent with the K_{ID} versus crack velocity relation. These findings suggest that T^*_ε could be a suitable ductile crack propagation and arrest criteria under rapid crack propagation while dynamic J and CTOA are not suitable dynamic fracture parameters..

References:

1] Brock, W. and Yuan, H., "Numerical Investigations on the Significance of J for Large Stable Crack Growth," *Engineering Fracture Mechanics*, 32 (3), pp. 459-468, 1989.

[2]. Dawicke, D.S., Sutton, M., Newman, J.C. and Bigelow, C.A., "Measurement and Analysis of Critical CTOA for Thin-Sheet Aluminum Alloy Materials," *Fracture Mechanics, Twenty-Fifth Volume,* ed. F. Erdogan, ASTM. STP 1220, pp. 358-379, 1995.

[3] Gang, H., Sutton, M. and Chao, Y.J., "A Study of Crack Tip Deformation Fields in Thin Sheets by Computer Vision," *Experimental Mechanics*, 34 (2), pp. 125-140, 1994.

[4] Li, S. and Chiang, F.-P., "Two-Parameter Characterization of Crack-Tip Field - An Experimental Study," *Twelfth U.S. National Congress of Applied Mechanics, Abstracts*, University of Washington, p. 395, 1994.

[5] Stonesifer, R.C. and Atluri, S.N., "On a Study of the (ΔT) and C^* Integrals for Fracture Analysis Under Non-steady Creep," *Engineering Fracture Mechanics*, 16, pp. 769-782, 1982.

2. Navy Relevance

Most of the naval structures are fabricated with ductile materials, such as medium strength steel and aluminum. While the utmost concern is to avoid catastrophic failure in the aging naval structures, a secondary concern is to predict the extent of maxmum crack extension or to design crack arresters in the event of a rapid crack propagation triggered by the unavoidable hostile environment. The popular J-integral criterion, currently in use by USN, has been shown by the PI and others to lack physical significance. On the other hand, the T^*_ε shows promise as a dynamic ductile crack propagation and an dynamic crack arrest criteria

3. ONR Technical Reports and Other Related Publications (Jan. 16, 1989 to present)

The 62 ONR Technical Reports and 74 papers, which were published through 31 January 1989 under the previous four ONR research contracts, are listed in the two ONR final reports; UWA/DME/TR-85/52 and UWA/DME/TR-89/64 and thus will not be repeated here. The following Technical Reports and publications were generated under the current contract of N00014-89-J-1276.

Technical Reports

B.S.-J. Kang, M.S. Dadkhah and A.S. Kobayashi, "J-Resistance Curves of Aluminum Specimens Using Moire Interferometry," Technical Report No. UWA/DME/TR-89/62, April 1989. *Proceedings of the 1989 SEM Spring Conference on Experimental Mechanics*, pp.317-322, 1989.

M. Dadkhah and A.S. Kobayashi, "HRR Field in An Aluminum SEN Specimen," Technical Report No. UWA/DME/TR-89/63, April 1989. Ibid loc cit, pp. 311-316, 1989.

M.S. Dadkhah, B.S.-J. Kang and A.S. Kobayashi, "J-Integral and HRR Field of a Stably Growing Crack, An Experimental Analysis," Technical Report No. UWA/DME/TR-65, April 1990. *Proceedings of Ninth International Conference on Experimental Mechanics*, Copenhagen, Vol. 5, pp. 1767-1775, Lyngby, Denmark, 1990.

M. Kosai and A.S. Kobayashi, "Axial Crack Propagation and Arrest in Pressurized Fuselage," Technical Report No. UWA/DME/TR-90/66. *Structural Integrity of Aging Airplanes*, eds. S.N. Atluri, S. Sampath and P. Tong, Springer-Velag, pp. 225-239, 1991.

R.H. Drinnon, Jr. and A.S. Kobayashi, "J-Integral and HRR Field Associated with Large Crack Extension," Technical Report No. UWA/DME/TR-90/67, December 1990. *Proceedings of 1991 SEM Spring Conference On Experimental Mechanics,* pp. 9-14, 1991.

K. Arakawa, R.H. Drinnon, M. Kosai and A.S. Kobayashi, "Dynamic Fracture Analysis by Moire Interferometry," Technical Report No. UWA/DME/TR-90/68. December 1990. Ibid loc cit, pp. 357-362, 1991.

M. Kosai, A.S. Kobayashi and M. Ramulu, "Tear Straps in Airplane Fuselage," Technical Report No. UWA/DME/TR-92/69. *Proceedings of Structural Integrity of Aging Airplane, Technological Publications*, Atlanta, 1993.

M.S. Dadkhah and A.S. Kobayashi, "An Experimental Study on the Two-Parameter Crack Tip Field," Technical Report No. UWA/DME/TR-92/70. Published as "Two Parameter Crack Tip Stress Field Associated with Stable Crack Growth in a Thin Plate, *Fracture Mechanics, 24 Volume*, ASTM STP 1207, eds. J.D. Landes, D.E. McCabe and J.A. M. Boulet, pp. 48-61, 1994..

G.B. May, F.X. Wang and A.S. Kobayashi, "Two-Parameter Crack Tip Field Associated with Stable Crack Growth in a Thin Plate--A Hybrid Analysis," Technical Report No. UWA/DME/TR-93-71

G.B. May, F.X. Wang and A.S. Kobayashi, "J-Integral and HRR Field Associated with Stable Crack Growth in Thin Aluminum SEN Specimen," Technical Report No. UWA/DME/TR-93-72. *Novel Experimental Techniques in Fracture Mechanics,* ed. A. Shukla, AMD-Vol. 176 ASME, pp. 145-152, 1993.

F.X. Wang, G. B. May and A.S. Kobayashi, "Steep Geometric Grating For Use in Moire Interferometry,," Technical Report No. UWA/DME/TR-93-73. Published as "Low-Spatial Frequency Steep Geometric Grating for Use in Moire Interferometry," *Optical Engineering,* vol. 33, no. 4, pp. 1125-1131, April 1994.

G.B. May and A.S. Kobayashi, Technical Report No. UWA/DME/TR-93/74 "Plane Stress Stable Crack Growth in J-integral/HRR Field," Dec. 1993. *International Journal of Solids and Structures*, Vol. 37, No.6/7, pp. 857-881, 1995.

Other Publications

K. Arakawa, R.H. Drinnon, Jr., F.X. Wang and A.S. Kobayashi, "Measurement of Dynamic Crack Opening Displacement by Moire Interferometry," *Transaction of the Japanese Society of Mechanical Engineers*, Vol. 58, No. 545, pp. 59-63, 1992.

K. Arakawa, R.H. Drinnon, M. Kosai and A.S. Kobayashi, "Dynamic Fracture Analysis by Dynamic Moire Interferometry," *Experimental Mechanics*, Vol. 31, No. 4, pp 306-309, 1991.

M.S. Dadkhah and A.S. Kobayashi, "HRR-Field of a Moving Crack, An Experimental Analysis," Technical Report No. UWA/DME/TR-88/60m September 1988. *Engineering Fracture Mechanics*, Vol. 34, No. 1, pp. 253-262, 1989.

M.S. Dadkhah and A.S. Kobayashi, "Further Studies of the HRR Field of a Moving Crack, An Experimental Analysis," Technical Report No. UWA/DME/TR-88/61, December 1988. *Journal of Plasticity*, Vol. 6, pp. 635-650, 1990.

M.S. Dadkhah, F.X. Wang, and A.S. Kobayashi, "Simultaneous On-Line Measurement of Orthogonal Displacement Fields by Moire Interferometry," *Experimental Techniques,* 12, 28-30, 1988.

M.S. Dadkhah, A.S. Kobayashi and W.L. Morris, "Crack Tip Displacement Fields and J_R Curves for Four Aluminum Alloys," *Fracture Mechanics: Twenty-second Symposium (Vol. II)*, eds. S.N. Atluri, J.C. Newman, Jr., J.S. Raju and J.S. Epstein, ASTM STP 1131, pp. 135-153, 1992.

R.H. Drinnon and A.S. Kobayashi, "J-integral and HRR Field Associated with Large Crack Extension," *Engineering Fracture Mechanics*, Vol. 41, No. 5, pp. 685-694, 1992.

F.X. Wang and A.S. Kobayashi, "High Density Moire Interferometry," *Optical Engineering*, Vol. 29, No. 1, pp. 38-41, January 1990.

L.R. Deobald and A.S. Kobayashi, "Dynamic Fracture Characterization of Al_2O_3 and SiC_w/Al_2O_3," *Journal of American Ceramic Society*, 75 (10), pp. 2867-70, October 1992.

C.T. Yu and A.S. Kobayashi, "Fracture Process Zone in SiC_w/Al_2O_3," *Ceramic Engineering and Science Proceedings Part 1 of 2*, pp. 273-281, July-August 1993.

Handbook on Experimental Mechanics, 2nd Revised Edition, ed. A.S. Kobayashi, VCH Publishers, 1993.

M. Kosai, A.S. Kobayashi and M. Ramulu, "Tear Straps in Airplane Fuselage," *Durability of Metal Aircraft Structures,* eds. S.N. Atluri, C.E. Harris, A. Haggard, N. Miller and S.G. Sampath, Technological Publications, Atlanta, GA, pp. 443-457, 1992.

A.S. Kobayashi, "Two Parameter Crack Tip Field Associated with Stable Crack Growth in a Thin Plate--A Hybrid Analysis," *Advanced Technology in Experimental Mechanics '93*, JSME, pp. 19-24, 1993.

A.S. Kobayashi, "Experimental Techniques in Micromechanics, An Update," ibid loc cit, pp.1-2.

H. Razi and A.S. Kobayashi, "Delamination in Composite Beams and Plates Subjected to Low Velocity Impact," *AIAA Journal*, Vol. 31, No. 8, pp 1489-1502, 1993.

C.-T. Yu, A.S. Kobayashi, and N.M. Hawkins, "Hybrid Experimental-Numerical Analysis in Fracture Mechanics," *Computer Aided Innovations of New Materials II*, eds. M. Doyama, J. Kihara, M. Tanaka and R. Yamamoto, Elsevier Science Pub., pp. 1161-1666, 1993.

Z.K. Guo and A.S. Kobayashi, "Hybrid Experimental-Numerical Analysis of Solids," *Third World Congress on Computational Mechanics*, Vol. II, Tezuka Microfilm Co., Tokyo, pp 1684-1689, 1994.

A.S. Kobayashi, "Hybrid Method in Fracture Mechanics," to be published in Hybrid Methods in Experimental Mechanics, ed. M. Takahashi, to be published in *Optics and Laser Engineering.*

A.S. Kobayashi, "Experimental Techniques in Dynamic Fracture," *Proceedings of International Symposium on Advanced Technology in Experimental mechanics*, JSME, pp 7-11, 1995.

J. Lee, M.T. Kokaly and A.S. Kobayashi, "Dynamic Ductile Fracture--An Experimental-Numerical Analysis," *Proceedings of VII International Congress on Experimental Mechanics*, SEM, pp. 445-446, 1996.

J. Lee, M.T. Kokaly and A.S. Kobayashi, "Dynamic Ductile Fracture of Aluminum SEN Specimens--An Experimental-Numerical Analysis," to be published in the *Proceedings of the Fifth Pan American Congress of Applied Mechanics*, San Juan, Puerto Rico, January 2-4, 1997.

J. Lee, M.T. Kokaly and A.S. Kobayashi,"Dynamic Ductile Fracture of Aluminum SEN Specimens - An Experimental-Numerical Analysis," to be published in the *Proceedings of the Ninth International Conference on Fracture*, Sydney, Australia, April 1-5, 1997.

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13. ABSTRACT *(Maximum 200 words)*

Geometric Moire and Moire interferometry were used to record the orthogonal displacement fields surrounding stably and rapidly propagating cracks in thin aluminum fracture specimens. The J- and T*-integral values were computed directly, for the first time, from the displacement data. J and T* were also obtained from static/dynamic, elastic-plastic finite element simulations of the fracture tests. While the ASTM far-field J increased, the near-field J precipitously dropped to zero with crack extension. The popular HRR elastic-plastic crack tip field also collapsed with crack extension. In contrast, the near-field T* reached a steady state value with crack extension and was found to be a suitable fracture parameter for characterizing stable and rapid crack growth and arrest.

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